In : Lee, Jeffrey A. and Zobeck, Ted M., 2002, Proceedings of ICAR5/GCTE-SEN Joint Conference, International Center for Arid and Semiarid Lands Studies, Texas Tech University, Lubbock, Texas, USA Publication 02-2 p. 271

Representation of Land-Surface Processes in Models of Wind Erosion

Michael R Raupach, CSIRO Land and Water, Canberra, ACT 2602, Australia (*Email: Michael.Raupach@csiro.au*)

Hua Lu, CSIRO Land and Water, Canberra, ACT 2602, Australia (*Email: Hua.Lu@csiro.au*)

Introduction

Quantitative assessment of wind erosion through mathematical modeling provides a useful tool to understand the spatial distribution and temporal dynamics of wind erosion and its impacts on climate and environmental changes. As much of the crucial action takes place at or just above land surfaces, a key issue is the correct representation of the land surface processes involved in particle uplift and deposition, and their dependencies on soil, vegetation and atmospheric variables.

This paper (of which the present abstract is a brief, incomplete summary) has two primary aims: to review the progress in key areas of process-based wind erosion and aeolian transport modelling during last decade, with an emphasis on surface processes, and to identify uncertainties and new research directions. Areas covered include (1) process-based saltation and dust emission models; (2) effects of vegetation on threshold friction velocity and dust uplift; (3) effects of vegetation on particle deposition; and (4) integrated wind erosion and dust transport modelling at large scales.

Saltation and Dust Emission Models

Sand grains saltating over a surface of loose fine particles excavate ovoid-shaped craters, by "saltation bombardment". Both field and wind tunnel experiments show that dust emission is mainly caused by this process. The resulting dust emission can be quantified by considering the relative values of sand-grain impact stresses on the surface and the soil surface strength. Lu (2000) showed that for typical values of impacting particle velocity and angle, the maximum surface pressure is about two orders of magnitude larger than the strength of the eroding soil surface. Under this condition, plastic deformation is the dominant mechanism for soil displacement. Lu and Shao (1999) derived an analytic dust emission model based on this idea, which yields the following prediction for the dust emission rate (for all dust particle sizes) caused by saltation of sand grains of diameter *d*:

$$F(d) = \frac{C_\alpha g f \rho_b}{2p}\left(0.24 + C_\beta u_* \sqrt{\rho_p / p}\right) Q(d) \qquad (1)$$

where $Q(d)$ is horizontal sand flux for particles with diameter d; $F(d)$ is the resulting vertical dust flux; ρ_p and ρ_b are the saltating-particle and soil bulk densities; u_* is the wind friction velocity; g is gravitational acceleration; f is the fraction of fine (dust) particles contained in the eroding soil; p is the plastic flow pressure of soil during impaction; C_α is the released fraction of dust contained in the volume removed by saltation bombardment; and C_β is a dimensionless coefficient. Integration of Equation (1) over a given sand particle size distribution gives the total dust emission rate. Lu and Shao (1999) showed that this model compares well with field measurements from sandy to sandy loam soils, but poorly for soils with surface structure, such as clay soils.

There are strengths and weaknesses of process based dust emission models, such as Equation (1). Strengths include (a) insight into the dependencies of dust emission processes on soil properties, wind speed, and the intensity of saltation; and (b) representation of supply limited dust emission through the parameters p, ρ_b, C_α and f, which relate to soil properties. Weaknesses include (a) issues in the application at large spatial and temporal scales, because of large-scale variability in microphysical parameters, and (more fundamentally) variability in the dominant basic processes; (b) difficulties in measuring or calculating parameters (although all parameters have physical meaning). For example, Lu (2000) showed by sensitivity analysis that the most sensitive parameter is p, which relates to the state of surface crusting but is very hard to measure. Its value changes with soil moisture and by freezing and thawing processes.

A model for dust emission by saltation bombardment depends on the existence of a saltation model. For transport-limited saltation over a loose sand surface, there is general agreement that the horizontal sand flux Q is proportional to $u_*^n[1 - f(u_*/u_{*t})]$ where u_{*t} is the threshold friction velocity for the eroding surface and $n = 3$. Different authors propose slightly different functional forms for the term $f(u_*/u_{*t})$ which accounts for the threshold of sand drifting (Greeley and Iversen 1985), subject to the requirements that $f = 1$ for $u_*/u_{*t} < 1$ (no drifting below threshold) and $f \rightarrow 0$ as $u_*/u_{*t} \rightarrow \infty$ (so that Q is proportional to u_*^3 at high wind speeds).

The situation for supply-limited saltation is not as clear, and depends on the mechanism by which the saltation supply is restricted. Possibilities include sheltering by vegetation (treated in the next section), moisture, and surface crusting.

Threshold Friction Velocity and its Dependence on Vegetation Cover

We first consider the inherent or bare-surface threshold velocity for particle uplift by wind, in the absence of vegetation. This is well known to depend on the balance of three forces: gravity, drag and interparticle cohesion (Greeley and Iversen 1985). Recent work (Lu and Raupach 2002) shows that consistent agreement with data for particle uplift in both air and water flows can be obtained from a simple expression of the form

$$\rho_a u_{*t}^2 = A\left[\left(\rho_p - \rho_a\right) g d + B/d\right] \tag{2}$$

where ρ_p and ρ_a are the particle and air densities, d is particle diameter and A and B are empirical coefficients. The first term in this expression accounts for the gravity-drag interaction (dominating the threshold condition for large particles) and the second for the drag-cohesion interaction (dominant for small particles). As shown in Figure 1, this expression is successful in predicting laboratory observations of u_{*t} both in air (with $A = 0.0123$, $B = 3\text{x}10^{-4}$ N m^{-1}) and in water (with $A = 0.05$, $B = 7.6\text{x}10^{-5}$ N m^{-1}).

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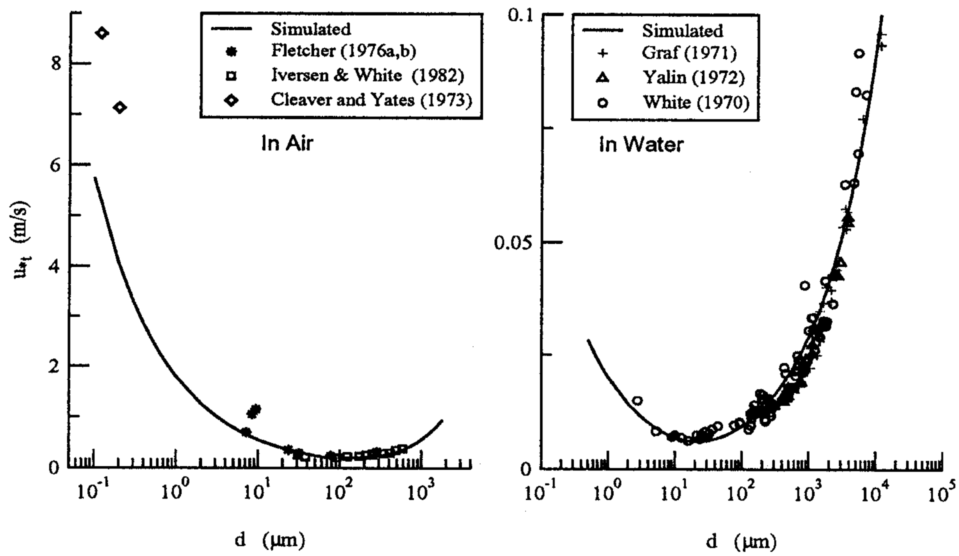

Figure 1: Comparison of predicted u_{*t} from Equation (2) with measurements in air and water.

Vegetation has major effects on threshold velocity. An initial estimate of these can be obtained from consideration of drag partition, the ratio of the stress on the ground surface to the total stress including both ground and vegetation. Raupach *et al.* (1993) used drag partition theory to produce a formula for the effect of vegetation on wind erosion threshold:

$$\frac{u_{*tS}^2}{u_{*tR}^2} = \frac{1}{(1-\sigma\lambda)(1+m\beta\lambda)} \quad (3)$$

where u_{*tS} and u_{*tR} are the threshold friction velocities for bare-soil and vegetated (roughened) surfaces, respectively, σ is the basal-to frontal area ratio, m is a parameter accounting for non-uniformity in the surface stress, and $\beta = C_R/C_S$, where C_R is the drag coefficient for isolated roughness elements and C_S is that for the soil surface. Recent work has generally confirmed the validity of this model, while suggesting revised interpretations of some coefficients (especially m) and better values for the drag coefficients C_R for standing vegetation elements.

Effects of Vegetation on Particle Deposition

Besides particle uplift, the other major surface process affecting particle transport by wind is deposition. In general, the particle deposition flux D to a surface can be represented as $D = W_dC$, where C is the particle concentration at a reference level above the surface and W_d is the deposition velocity. This is a transfer coefficient which can be expressed as a parallel sum of conductances over three pathways, gravitational settling (at terminal velocity W_t), impaction (with conductance G_{imp}), and Brownian diffusion (with conductance G_{brow}). Thus, $W_d = W_t + G_{imp} + G_{brow}$. These terms depend quite differently on particle diameter, with deposition being dominated by settling for large particles, impaction for particles in the range 1 – 50 μm, and Brownian diffusion for very small particles. The impaction and Brownian-diffusion conductances are strong functions of surface roughness, in ways that can be described well by a simple, single-layer model (Raupach *et al.* 2001); see Figure 2.

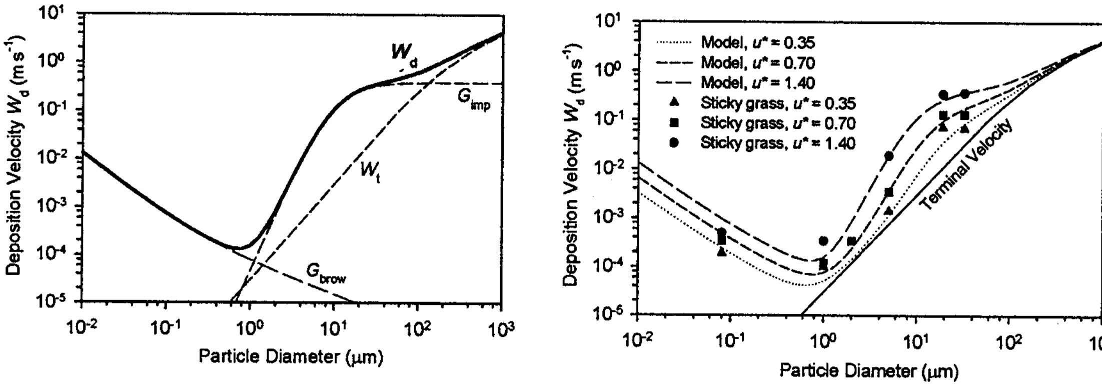

Figure 2: (Left panel) Typical contributions of the three terms W_t (settling), G_{imp} (impaction) and G_{brow} (Brownian diffusion) to the deposition velocity W_d. (Right panel) Test of a single-layer model for the deposition velocity W_d against wind tunnel measurements of particle deposition to a sticky grass surface. See Raupach *et al.* (2001) for details.

Integrated Wind Erosion and Dust Transport Modelling

The dust emitted during wind erosion affects the global climate changes and energy balance. Predicting these effects requires quantitative estimations of the spatial and temporal variations of the source location, rate, transport pathways and deposition area of the dust. One way to model the systems behavior of dust transport is through an integrated system coupling an atmospheric model, a dust emission model, a dust transport and a dust deposition model and linking to a GIS data base. Such integrated approaches have been applied to simulate dust storms at regional to continental scale (Shao and Leslie 1997; Lu and Shao 2001). The parameterization of large-scale models of this kind is not simple, but a path forward is offered by "model-data fusion" approaches now being implemented in earth system science.

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